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Measurements of the Distribution and Volume of Sea-Surface Oil Spills Using Multifrequency Microwave Radiometry

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ABSTRACT

Multifrequency passive microwave measurements from aircraft have been made of eight controlled marine oil spills. It was found that over 90 percent of the oil was generally confined in a compact region with thicknesses in excess of 1 mm and comprising less than 10 percent of the area of the visible slick. It is shown that microwave radiometry offers a means to measure the distribution of oil in sea-surface slicks and to locate the thick regions and measure their volume on an all-weather, day-or-night, and real-time basis.

PROBLEM STATUS

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MEASUREMENTS OF THE DISTRIBUTION AND VOLUME OF SEA–SURFACE OIL SPILLS USING MULTIFREQUENCY MICROWAVE RADIOMETRY

There is mounting concern by the public and governmental agencies over the ever-increasing number of marine oil spills and the more serious resulting pollution. Before appropriate corrective action can be taken, a knowledge of the nature, thickness, areal extent, direction, and rate of drift of the oil spill must be promptly established. This requires a detection and measurement system capable of rapidly responding to a requirement of surveying large and often remote and inaccessible waters on a nearly all-weather and day-or-night basis.

Reliable determination of oil-film thickness is of major importance. It is the film thickness along with areal extent which allows the volume of the slick to be estimated. A knowledge of the volume of oil is essential for litigation and damage claims resulting from major oil spills, as well as for assessing the impact of the spill on marine life and environment. A knowledge of the oil distribution and the location of those regions containing the heaviest concentration of oil would enable the most effective confinement, control, and clean-up of the oil and perhaps is most important.

Sea-surface oil spills do not spread uniformly nor without limit (1, 2). Thick regions which contain the majority of oil are formed and are surrounded by very much thinner and larger slicks. For example, in controlled oil spills of 200 to 630 gallons (760 to 2380 liters), which will be described in detail later, the oil typically formed a region with a thickness of 1 mm or more containing more than 90 percent of the oil but comprising less than 10 percent of the area of the visible slick. The remaining oil formed a large slick, hundreds of times thinner, surrounding the thick region.

Microwave radiometry offers a unique potential for determining oil-slick thicknesses greater than about 0.05 mm. The apparent microwave brightness temperature is greater in the region of an oil slick than in the adjacent unpolluted sea by an amount depending on the slick thickness. In effect the oil film acts as a matching layer between free space and the sea enhancing the brightness temperature of the sea. The calculated* increase in microwave brightness temperature due to an oil slick above that due to the unpolluted sea as a function of slick thickness is shown in Fig. 1 for the three microwave frequencies at which measurements were made. As the thickness of the oil film is increased, the apparent microwave brightness temperature at first increases and then passes through alternating maxima and minima, due to the standing-wave pattern set up by the sea surface. The maxima and minima occur at successive integral multiples of a quarter wavelength in the oil. By using two or more frequencies, thickness ambiguities introduced by the oscillations can be removed and the film thickness determined for a wide range of thicknesses.

* The reflection coefficients for a smooth dielectric material covered by a uniform dielectric film of finite thickness, necessary to calculate the brightness temperature, are given in Ref. 3.

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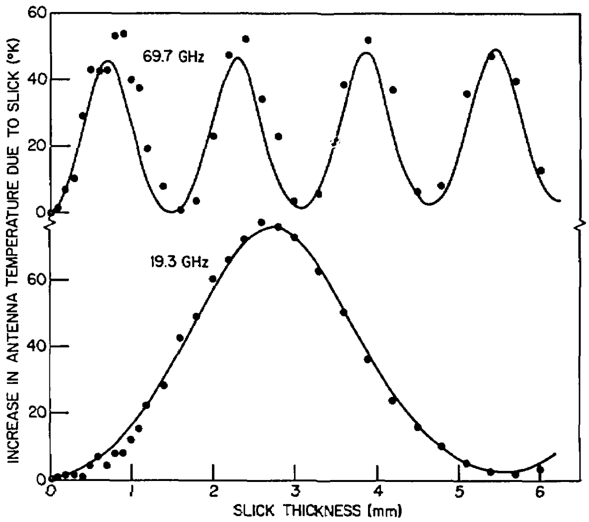

Fig. 2 — The data are measurements at 19.3 and 69.8 GHz of the increase in antenna temperture due to No. 2 fuel oil spread over a smooth water surface in a test tank as a function of film thickness. The curves represent the calculation which best fit the measurements.

where f (θ,φ) is the normalized antenna response pattern and T_B (θ,φ) is the total brightness temperture in the direction θ,φ and is composed of not only the radiation emitted by the sea surface but also the downwelling sky radiation reflected by the surface as well as the emission and attenuation of the atmosphere between the surface and the radiometer. Atmospheric effects are usually less than 10 percent for observational frequencies away from the water-vapor absorption line at 22.235 GHz and below about 40 GHz, and in general approximate corrections can be applied to partially remove them.

A series of eight controlled oil spills was conducted during the period August 1971 through August 1972 in cooperation with the NASA-Wallops Island Station, the Virginia Institute of Marine Science, and the U. S. Coast Guard to investigate the possiblity of determining the thickness of an oil slick using passive microwave radiometry. The spills, of from 200 to 630 gallons (760 to 2380 liters) of either No. 2 fuel oil or No. 4 or No. 6 crude oil, were performed in accordance with the guidelines established by the Environmental Protection Agency for the discharge of oil for research purposes (5). All of the spills were conducted in relatively calm sea conditions of less than 2-m swell and 10-m/s surface winds. The oil was transported in 50-gallon (190-liter) drums to the ocean test site, about 10 mi (16 km) east of Chesapeake Light Tower off the east coast of Virginia. The drums were off-loaded, herded together, and emptied from small rubber boats in a manner so as to obtain as nearly an undistrubed point release as possible.

The documentation of "ground truth" gathered included the type and volume of oil spilled, in situ measurements of oil-slick thickness, and airborne natural and color IR photography and thermal IR imagery, as well as the environmental parameters of sea temperature, air temperature, relative humidity, wind speed and direction, sea state, and general weather and cloud conditions. The oil in two spills was dyed with an oil-soluable

Table 1
Measured Complex Dielectric Constant of Oil

Oil Type	Temperature (°C)	Complex Dielectric Constant	
		f = 19.3 GHz	f = 69.8 GHz
No. 2 Fuel	19	ϵ_1: 2.10 ± 0.05	ϵ_1: 2.10 ± 0.05
		ϵ_2: $0.01^{+0.02}_{-0.01}$	ϵ_2: $0.01^{+0.02}_{-0.01}$
No. 4 Crude	26	ϵ_1: 2.4 ± 0.1	ϵ_1: 2.2 ± 0.1
		ϵ_2: 0.06 ± 0.04	ϵ_2: 0.07 ± 0.04
No. 6 Crude	26	ϵ_1: 2.6 ± 0.2	ϵ_1: 2.6 ± 0.2
		ϵ_2: 0.05 ± 0.05	ϵ_2: 0.05 ± 0.05

red dye to aid in establishing the distribution of oil over the sea surface. The dye allowed the thick regions of oil to be easily identified visibly. Figure 3 is a series of drawings traced from color photography of the July 11, 1972, oil spill. This spill consisted of 630 gallons (2380 liters) of No. 2 fuel oil dyed red. The sea conditions were calm, with about 1-m swell and winds of 2 - 4 m/s. The outer line in each drawing represents the extreme edge of the visible slick, the next inner line is the region of color fringing when visible in the photograph, and the crosshatched area is the region of thick oil. The oil formed a well-defined thick region surrounded by a very much larger and thinner region. In situ thickness measurements showed the oil to be 2.4 ± 0.3 mm thick at spots in the crosshatched region and typically 2 to 4 μm thick outside this region. The thick inner region spread at a much slower rate than the total slick. This is shown in Fig. 4 where the area of the inner region and the total area of the visible slick are displayed as a function of time on a log-log plot. If the dashed lines are taken to represent the measurements, the total area grew at a rate proportional to the time to the 0.6 power; the thick region grew at a rate proportional to time to the 0.2 power. The spreading rate of the total area most nearly matches the gravity-viscous spreading phase described theoretically by Fay (6), which grows at a rate proportional to the square root of the time. It is somewhat slower than spreading rates reported by Guinard (7) or by Munday et al., (8). However the spreading rate is dependent on many variables—such as initial volume, age, density and viscosity of the oil, the surface-active materials present, interfacial surface tension, surface wind, sea state, and surface current present—and will vary widely. Most significant is the dichotomous behavior of the oil, dividing clearly into a thick, relatively compact region surrounded by a second much larger and thinner region. All of the spills conducted of each oil type exhibited this behavior. It may well be due to small quantities of surface-active materials in the oil which spread more rapidly than the bulk of the oil, surrounding it, inhibiting its growth, and thus containing and controlling the oil.*

The microwave observations were taken using the NASA-Wallops Island DC-4 aircraft. Measurements were made at 19.4 and 69.8 GHz for the initial spills and at 19.4 and 31.0

* Private communication with W. D. Garrett.

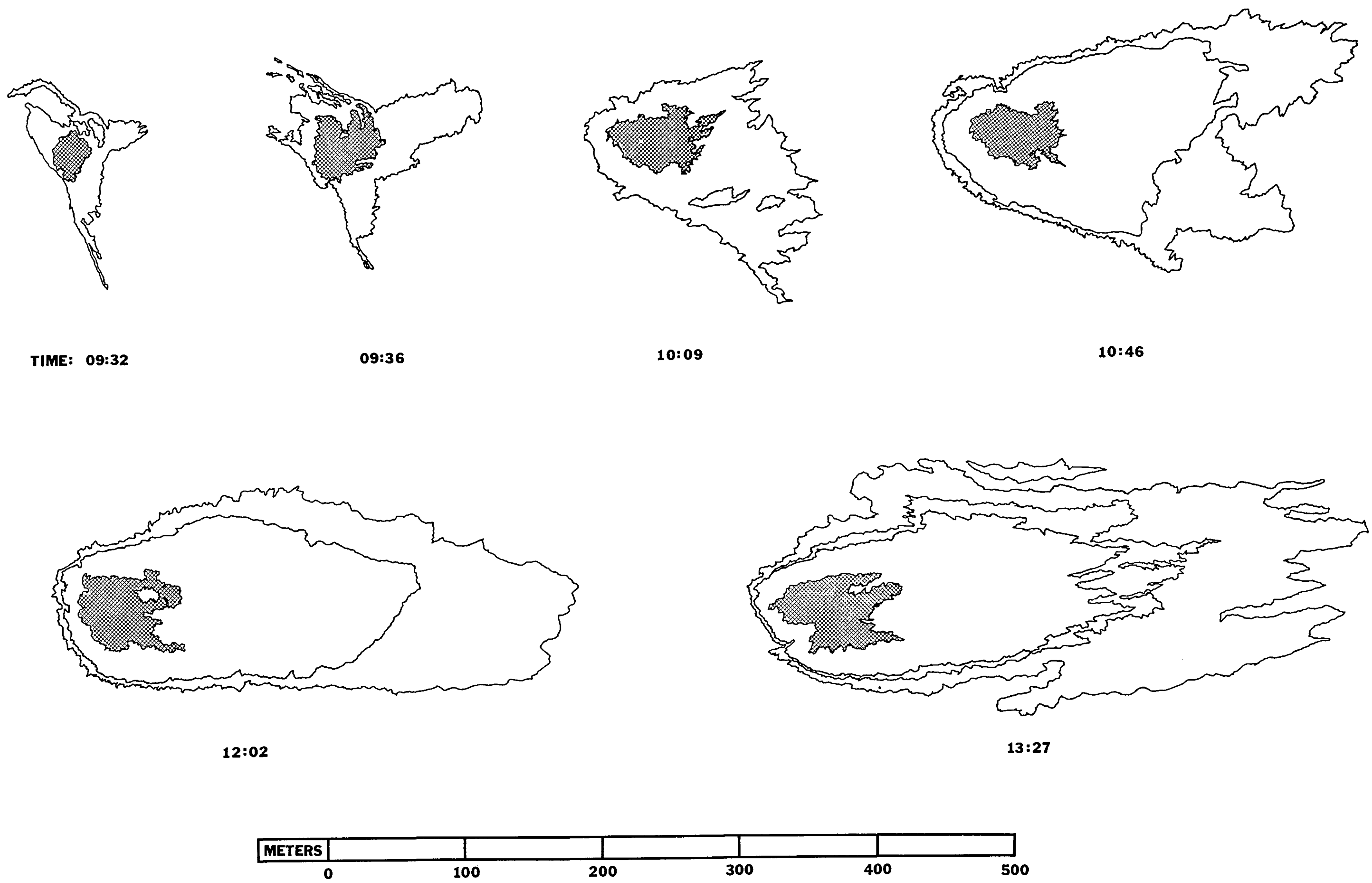

Fig. 3 — Tracings of color photography of the oil slick resulting from a controlled oil spill of 630 gallons of No. 2 fuel oil. The oil had been dyed red to allow the thick regions of oil to be identified visibly. The outer line in each drawing represents the extreme edge of the visible slick, the next inner line is the region of color fringing when visible in the photograph, and the crosshatched area is the region of thickest oil.

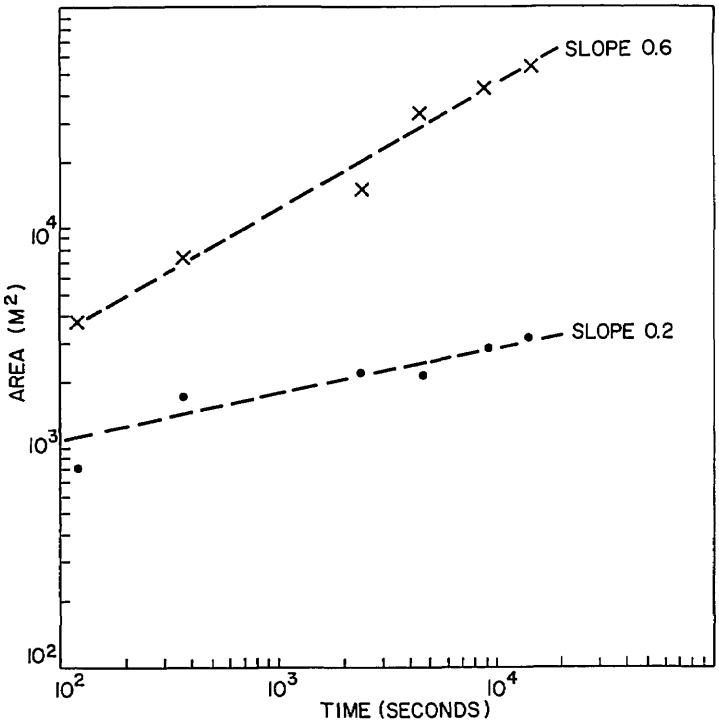

Fig. 4 — Area of the inner thick region (dots) and the total area of the visible slick (crosses) measured from the photography of the oil spill represented in Fig. 3 is plotted versus the time the picture was taken. The dashed lines are possible representations of the measurements.

GHz for the last three spills. The latter combination proved more effective for the oil thicknesses of up to several millimeters which were encountered. The half-power antenna beamwidth at all three frequencies was 7.2 degrees, which gave a beam spot on the surface of about 50 ft (15 m) for the aircraft altitude used of about 400 ft (122 m). A two-dimensional antenna-temperature map of the oil slick was built up by making repeated aircraft passes over the extent of the slick. Approximately 15 to 30 minutes before and after the nominal time of the map were required to acquire sufficient scans for the map.

Contour maps of the increase in antenna temperature above that for the unpolluted sea at 19.4 and 31.0 GHz are shown at the right in Fig. 5 superimposed on the outline of the visible slick for the spill of July 11, 1972. These antenna-temperature distributions were used to derive the thickness contours shown at the bottom left of the figure. The antenna temperatures and derived thicknesses are weighted averages over the antenna beam, as given by Eq. (1). The half-power beam spot on the surface is represented by the small circle. The microwave signals coincide closely with the region of thick oil and show that average thicknesses over the antenna beam of up to 1.5 mm are present in good agreement with in situ spot measurements in this area of 2.4 ± 0.3 mm. Integration of the thickness contours derived from the microwave data gives a volume of 650 ± 65 gallons (2460 ± 246 liters), which taken with the volume of oil spilled of 630 gallons (2380 liters) indicates that nearly all of the oil is in the thick region. This is consistent with in situ measurements of film thicknesses of 2 — 4 μm outside the thick region, since only 15 to 30 gallons (57 to 114 liters) of oil would be needed to cover the entire

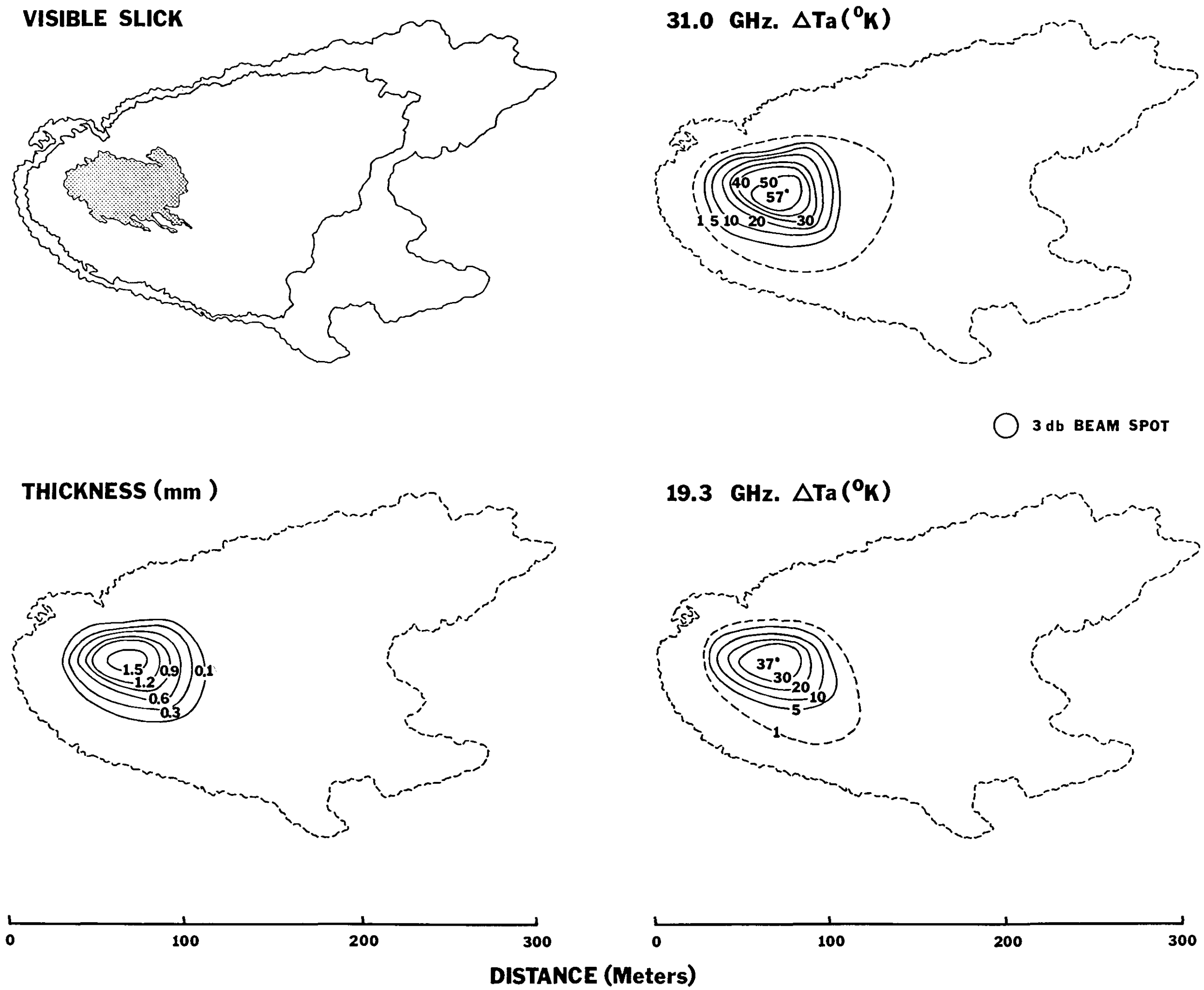

Fig. 5 — The upper-left-hand drawing is a tracing of a color photograph of the oil slick resulting from a controlled spill of 630 gallons of No. 2 fuel oil. The oil had been dyed red to allow the thick regions of oil to be identified visibly. The outer line is the extreme edge of the visible slick, the next inner line is the region of color fringing, and the crosshatched area is the region of thick oil. The antenna temperature measured at 19.3 and 31.0 GHz are shown at the right superimposed on the outline of the visible slick. The thickness contours derived from the microwave data are shown at the bottom left.

area of the visible slick of 33×10^3 m^2 with a uniform film to thicknesses of $2 - 4$ μm. The ratio of slick thickness in the two regions of nearly 1000 also shows that nearly all of the oil is located in a small region of the slick.

The microwave measurements of all of the oil spills of each oil type showed results very similar to those just described for the spill of July 11, 1972. The slicks always formed an identifiable region with film thicknesses of a millimeter or more and containing the majority of oil, which was surrounded by a very much larger and thinner slick which contained very little of the oil. In general the thick region contained more than 90 percent of the oil in less than 10 percent of the area of the visible slick. It was always possible to locate and delineate the thick region solely form the microwave observations, and the total volume of oil present derived from the microwave measurements was within about 25 percent of the volume of oil spilled.

In summary, multifrequency passive microwave radiometry offers the potential to measure the distribution of oil in sea-surface oil slicks and to locate the thick regions and measure their thickness and volume on an all-weather, day-or-night, and real-time basis. As such it should prove a useful tool in the confinement, control, and cleanup of marine oil spills.

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13. ABSTRACT

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